ON VOLTAGE STABILIZER CIRCUITS*

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(*Received for publication, November 4, 1941*)

ABSTRACT The paper describes several improved forms of voltage stabilizer circuits. The single-valve and the two-valve Neher Pickering circuits have been improved by reducing the number of dry batteries used, without in any way sacrificing the performance. New principles are applied to the usual two-valve stabilizer circuit by which it is possible to have "perfect" stabilization and "zero" or negative internal resistance. A circuit is described which is suitable for supplying a stabilized current to the heaters of the thermionic tubes used in sensitive valve voltmeters. The performance of the circuit is very much superior to that of the stabilizing transformers and baretter tubes as regards the stabilization.

The effect of source resistance on the performance of stabilizers has been studied. The analysis has the advantage of being not only more general but also more simple and straightforward.

CONTENTS

* Communicated to the Indian Physical Society.

1. INTRODUCTION

A source of constant voltage is necessary for various physical and technological experiments and measurements. Ordinarily, storage or dry batteries are used for this purpose. They are, however, inconvenient and expensive and very much so when high voltages are required.

Stabilizer circuits of various types have therefore been developed to perform the function of the battery of dry or storage cells. The circuits employ only a few low voltage dry batteries, one or a few thermionic valves and some resistances. The voltage of the primary source, from which power is taken, may be fluctuating over a wide range but the output voltage V_0 from the stabilizer remains more or less constant ; its variation, with the variation of the input voltage V_i, is reduced very much in proportion. If the current I_0 drawn from such a stabilizer is changed, the output voltage V_0 changes even when the input voltage is held constant. The variational performance of the stabilizer circuit can thus be represented by the values of $\left(\frac{dV_i}{dV_0}\right)$ and of $\left(\frac{\partial V_0}{\partial I_0}\right)_{V_i}$. $\left(\frac{dV_i}{dV_0}\right)$ is called the stabilization factor and is designated by S_0, while the negative of $\left(\frac{\partial V_0}{\partial I_0}\right)_{V_i}$ gives the internal resistance R_0 of the stabilizer in analogy with that of a battery.

The stabilizer circuits can be classified into four groups according to their derivation from :[1]

(*a*) the amplification factor bridge (μ circuits),
(*b*) the transconductance bridge (S circuits),
(*c*) the degenerative amplifier (D circuit),
and (*d*) combination circuits involving two or more of the foregoing classes.

The most notable of these circuits are the one described by Evans[2] and two others described by Neher and Pickering.[3] These circuits are widely used but they suffer from certain defects. Thus the Evans circuit, which is a μ circuit employing a pentode, has a very high internal resistance. It is therefore not suitable for applications requiring a constant voltage under varying current drains. Also the output voltage can be varied only over a small range as otherwise the balance conditions will be upset.

Again, of the two Neher-Pickering circuits, the first one, which is an S circuit modified by the inclusion of a series resistance, though capable of giving excellent performance, particularly with systems requiring negligible current drains at high voltage (G. M. counters, etc.), suffer from the disadvantage of having two dry batteries, and also have a relatively high internal loss of voltage.

The second circuit of Neher and Pickering is also very good in the sense that it is capable of giving very high stabilization ratios and is suitable for large current drains; but its most serious obstacle to general use is that it employs four dry batteries, one of which has to be very thoroughly insulated and shielded.

In the present investigation the author has first effected certain improvements on the Neher-Pickering circuits removing some of their common defects. These are described in § 2. He has further introduced modifications to the usual two-valve stabilizer circuits by which it has been possible to have "perfect" stabilization and "zero" or negative internal resistance. These, along with a circuit suitable for supplying a stabilized current to the heaters of thermionic tubes as are used in sensitive valve voltmeters, are described in § 3. The effect of source resistance on the performance of stabilizers is investigated in § 4.

2 MODIFICATIONS ON THE NEHER-PICKERING CIRCUITS

(*a*) *Single valve circuit.* The first circuit of Neher and Pickering is modified to the form shown in Fig. 1. The improvement consists in eliminating the screen battery. The screen grid is supplied from a potentiometer connected across the input voltage terminals. But, as will be seen presently, in spite of this, the screen voltage remain constant, independent of fluctuations of the input voltage.

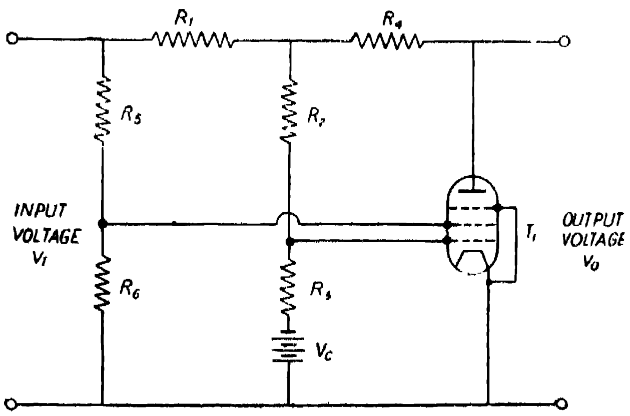

FIG. 1

Modified form of the single-valve Neher-Pickering circuit The screen battery is replaced by a potentiometer connected across the input terminals.

The action of the circuit is as follows. As the input voltage is increased from a very low value, the output voltage continually increases, until at a value

$$V_i' = \left[V_0 + (V_0 + V_c) \frac{R_1}{R_2 + R_3} \right]. \qquad \ldots \quad (1)$$

The output voltage becomes equal to V_0, the stabilized voltage required, given by the relation *

$$V_0 = \left[\frac{R_2}{R_3} \cdot (V_c - \epsilon) - \epsilon \right]. \qquad \ldots \quad (2)$$

ϵ is the negative grid voltage at which the tube just begins to take current. Before this, none of the positive electrodes—the screen grid or the anode—takes any current. When the input voltage is equal to V_i', the screen voltage becomes equal to

$$V_s = \frac{R_6}{R_5 + R_6} \cdot V_i'. \qquad \ldots \quad (3)$$

As the input voltage is increased still further, the tube takes current simultaneously through the anode and the screen. The anode current is given by the relation

$$I_a = \frac{V_i - V_i'}{R_1}.$$

Assuming the screen current to be a constant fraction of the anode current, we have

$$I_s = \frac{V_i - V_i'}{R_1}. \qquad \ldots \quad (4)$$

If no screen current were taken by the tube, the voltage across R_6 would increase to the value $V_i . \frac{R_6}{R_5 + R_6}$. But due to the screen current, the actual voltage will be smaller and may, by suitable choice of R_5 and R_6, be made exactly the same as it was previously, *viz.*, that given by (3). The method of calculation of the proper values of R_5 and R_6 is indicated below.

By Thevanin's theorem, the screen supply system may be replaced by the simple circuit having the constants as shown in Fig. 2. The condition to be

* The relation $V_0 = \frac{R_2 + R_3}{R_3} . (V_c - \epsilon)$ holds in the case when the battery is connected between the junction of R_2 and R_3 and the grid of the tube T_1.

satisfied is, therefore,

$$\frac{R_6}{R_5+R_6} \cdot V_i - R_s I_s = V_s. \qquad \dots \quad (5)$$

Next we are to prove that if equation (5) is satisfied at one value of V_i, it will hold for other values as well.

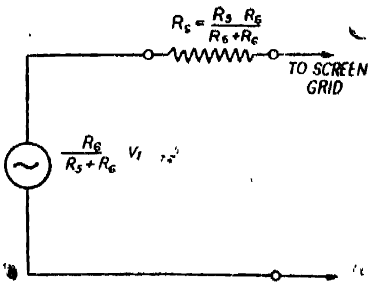

FIG. 2

Equivalent electrical circuit of the screen supply system

In other words, eq. (5) should be independent of V_i. Let us substitute eq. (4) in eq. (5). We get, after simplification,

$$\frac{R_6}{R_5+R_6} \cdot V_i - \frac{R_s a}{R} V_i + \frac{R_s a}{R_1} V'_i = V_s. \qquad \dots \quad (6)$$

It is clear that the above equation will be independent of V_i, if

$$\frac{R_6}{R_5+R_6} = \frac{R_s a}{R_1}. \qquad \dots \quad (7)$$

The other equality which equation (6) leads to is also satisfied by Equation (3).

The appropriate values of R_5 and R_6 can be calculated with the help of equations (3) and (7). They are

$$R_5 = \frac{R_1}{\text{[illegible]}} \quad \text{and} \quad R_6 = \frac{R_1}{a\left(\frac{V_i'}{V_s} - 1\right)} \qquad \dots \quad (8)$$

It will be observed that the value of R_5 is independent of the voltages V_s or V_0. So that if the output voltage is changed by changing either R_3 or V_c, the value of R_5 need not be changed. But the value of R_6 will have to be changed so as to make a the same as before, as a depends on the screen and the anode voltages.*

For the sake of comparison, a circuit was set up, using nearly the same component values as were used by Neher and Pickering. The performance of the circuit, with a screen battery of 53 volts and with a potentiometer holding the screen voltage constant at 51 volts, is shown in the curves of Fig. 3. The effectiveness of the circuit in stabilizing its own screen voltage will be appreciated if a comparison is made between the screen voltage—input voltage curves depicted in Fig. 4.

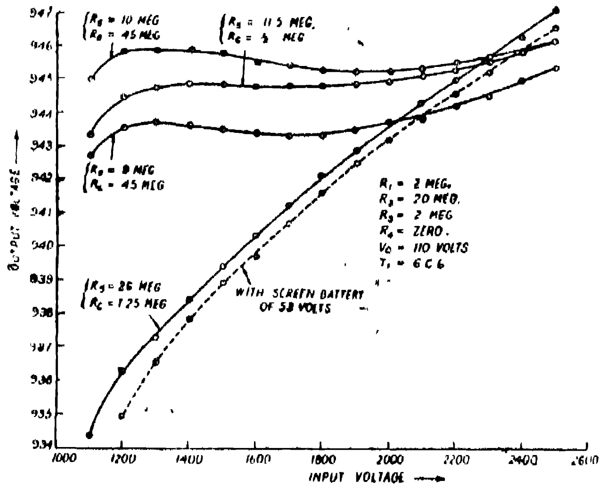

FIG. 3

Stabilization characteristics of the circuit of Fig. 1 for different values of the screen supply resistance. The curves for $R_5 = 11 \cdot 5$ Meg. and $R_6 = \frac{1}{2}$ Meg. shows that the output voltage variation is less than 0.1 volts over the input voltage range of 1400—1900.

The performance of the circuit can be considerably improved by utilising the screen grid as another control element of the stabilizer as described below.

The values of R_5 and R_6 may be so chosen that the screen voltage, instead of remaining constant, increases steadily with the input voltage. Under such condition the control applied to the screen grid forms a *transconductance* type stabilizer circuit and stabilizes the voltage at the output terminals even when no control

* The screen current is not merely the primary electron current but may be greatly modified by secondary electrons ejected from the screen grid. These are drawn through the suppressor grid when a sufficiently high voltage is on the anode. The primary electron current, however, bears a constant ratio with the anode current, whatever may be the anode and screen voltages.

is applied to the grid. A transconductance circuit gives perfect stabilization when the relation

$$C\,S_m = \frac{1}{R_1} \qquad \ldots \quad (9)$$

is satisfied. C gives the rate at which the voltage on the grid of the tube (in our case the screen grid) changes with change of the input voltage. Thus

$$C = \frac{d\,V_s}{d\,V_i};$$

S_m is the transconductance between the electrodes, being, in our case, the screen grid to anode transconductance.

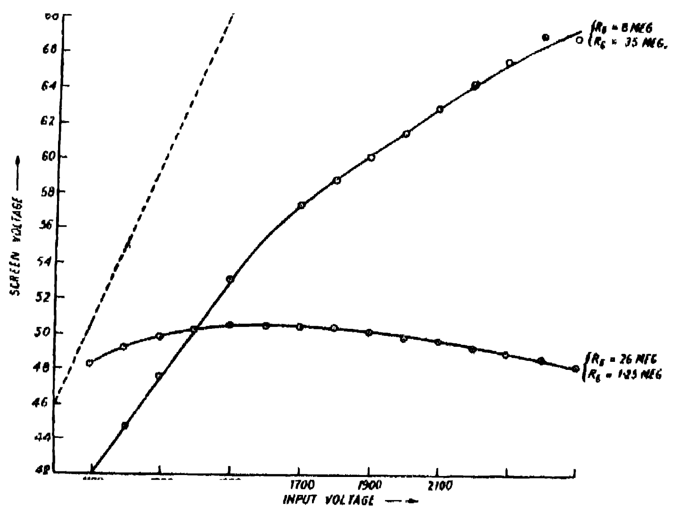

FIG. 4

Variation of screen voltage of the tabilizer tube with input voltage. It is to be noted how tb e variation of the screen voltage can be reduced by using suitable values ($R_5 = 26$ Meg. and $R_6 = 1.25$ Meg.) of the scieen supply resistances. The dotted curve shows the variation of voltage across a potentiometer of 26 Meg. and 1.25 Meg

In the usual type of transconductance circuit where the control is applied to the grid maintained at a negative potential, the value of C is constant. In such a circuit the condition of perfect stabilizaticn is satisficd at one value of the input voltage, *viz.*, where S_m has the value given by equation (9). At other values of the input voltage, the current through the tube being different, the transconductance is also different. As a result, such a circuit gives a high stabilization factor only over a small range on both sides of the input voltage where the condition given by the equation (9) is satisfied. In a screen grid anode transconductance so as to make a the same as before, as a depends on the screen and the anode voltages.*

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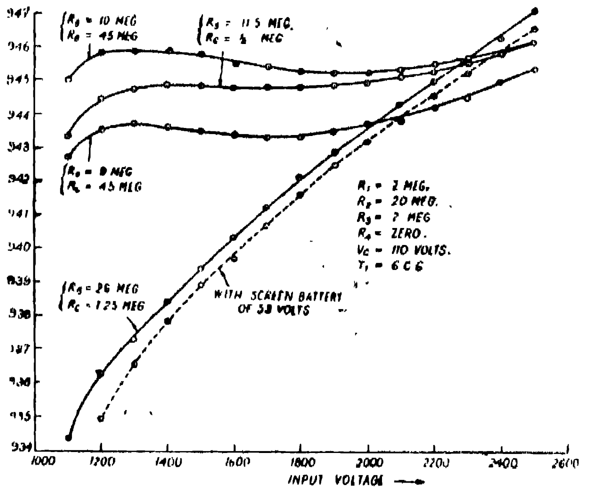

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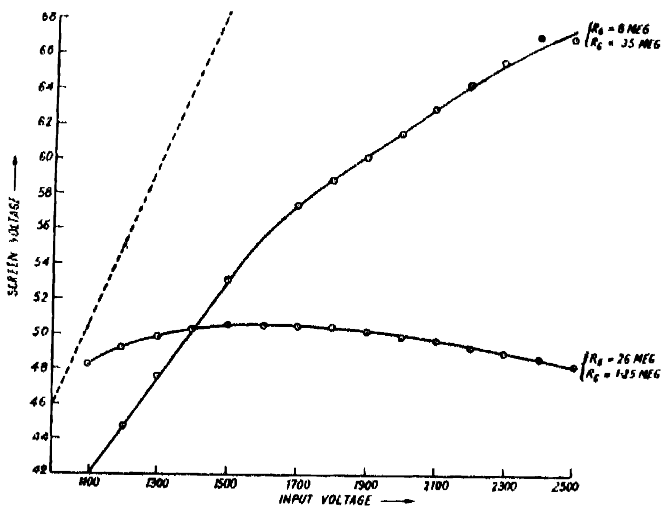

FIG. 4

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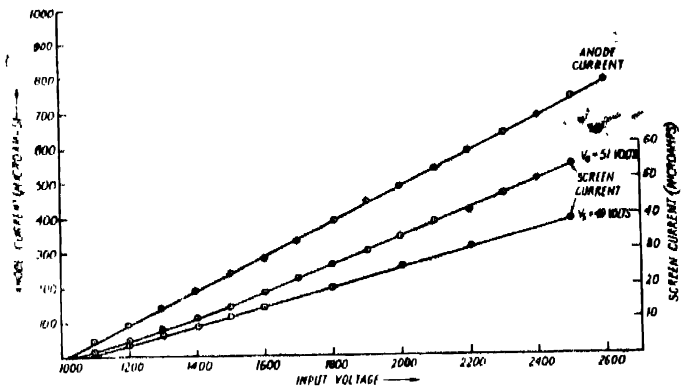

FIG. 5

Variation of the anode and screen currents of the stabilizer tube with input voltage.

input voltage V_i as will be seen from the two screen current curves in fig. 5, although it is still appreciable. If, however, the screen voltage increases with the input voltage, the increase in magnitude of $\frac{\partial I_s}{\partial V_i}$ becomes considerable as may be judged by comparing the two curves of Fig. 5. The result of this is to diminish the value of C as the input voltage increases. (See the screen voltage—input voltage curve for $R_5=8$ Meg. and $R_6=.35$ Meg. in fig. 4.) This diminution of C with the input voltage may cause eq. (9) to be satisfied again at a higher value of input voltage giving perfect stabilization at another point on the higher voltage side as is depicted by the curves in Fig. 6. With a suitable choice of the values of R_5 and R_6 these two regions can be brought sufficiently close together giving high stabilization over a considerably wide range of voltages. Thus in the curve of $R_5=11.5$ Meg. and $R_6=\frac{1}{2}$ Meg. where this condition is obtained, the output voltage varies by only 2 volts over a range of 300 volts. The dotted curve shows the nature of the stabilization characteristic if there were no screen current.

When control is applied both to the grid and to the screen grid, the stabilization curves become, as may be expected, very much better. This is shown in fig. 3. The curve for the circuit in which $R_5=11.5$ Meg. and $R_6=\frac{1}{2}$ Meg. keeps the output voltage constant within 0.1 volt over the range of 1,400-1,900 volts. The resistance R_4 of the original Neher-Pickering circuit gives no advantage and is unnecessary. Better performance can be obtained even without it,

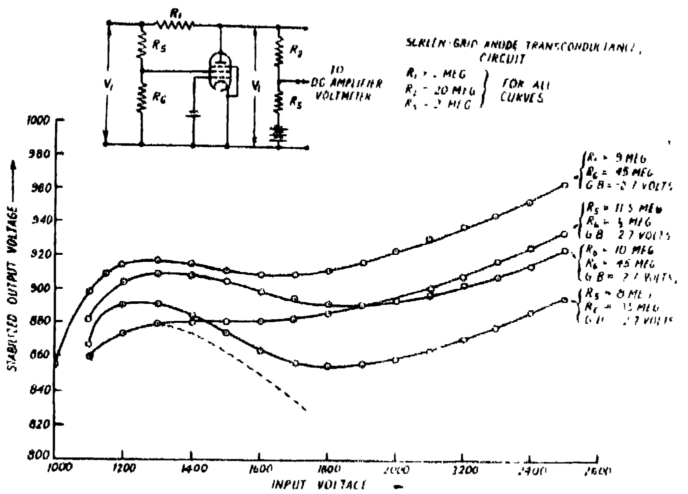

FIG. 6

Stabilization curves of the transconductance circuit which is formed when the screen voltage is supplied by a potentiometer

Experimental arrangement for testing the performance. The stabilizer circuit described above is ordinarily called upon to deliver small currents. Further, since the stabilization characteristics of the circuit are dependent on the value of the current drawn, it is necessary that the measuring instrument employed should consume little or no current. Accordingly a valve voltmeter may be used to measure the variations while the steady component is balanced out. Since the output voltage is high, it is convenient to make the measurements on a known fraction of the output voltage across a high resistance potential divider. A suitable arrangement is in the stabilizer circuit itself, *viz.*, the resistance R_2, R_3 and the battery V_r (Fig. 1). The voltage variations across the grid cathode of the stabilizer tube may therefore be measured for testing the performance. A specially designed valve voltmeter was used for this purpose. The circuit was similar to that of the one described by Roberts[4] and incorporated a variable degeneration resistance which was used as a sensitivity control.

(*b*) *Two-Valve Circuit.* The two-valve circuit of Neher and Pickering gives much better performance than the single-valve circuit. It has a higher stabilization ratio, lower internal resistance and is also capable of delivering large currents. The circuit, however, has the disadvantage that it requires as many as four dry batteries of which one has to be insulated very thoroughly.

The modified form uses only two batteries none of which demand very thorough insulation. The performance of the modified circuit, instead of deteriorating, is actually somewhat improved. The circuit is shown in Fig. 7.

It will be observed that the screen battery E_{s_2} and the grid battery E_{g_1} of the Neher-Pickering circuit have been eliminated. The arrangement for the screen supply of T_2 as used here is more convenient than a tap across R_2 as suggested by Neher and Pickering in the sense that it is now possible to change the output voltage by changing R_2, without affecting the screen voltage. The screen voltage is equal to $(V_1 - \epsilon)$, where ϵ is the grid voltage at which the tube T_2 operates. Not only does this method of connection save one battery, but actually it improves the performance although only by a small amount. Here the control is applied both to the grid and the screen grid as a result of which the effective gain G of the tube T_2 increases by about 5 to 6 per cent and with it the stabilization ratio.*

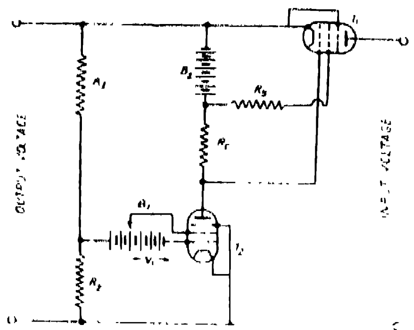

FIG. 7

Modified two-valve Neher-Pickering circuit. The two batteries in the circuit perform the duties of the four used in the original one.

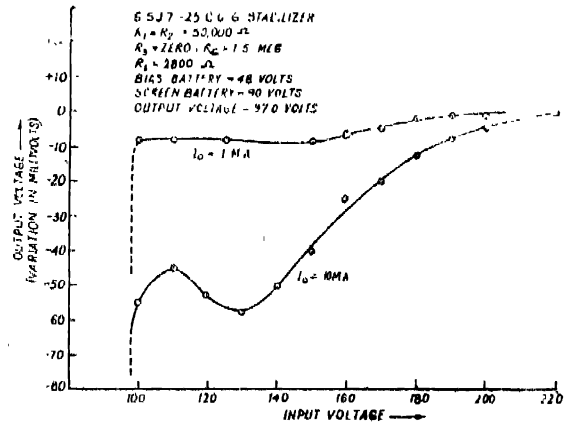

FIG. 8

Stabilization curves of the modified two-valve Neher-Pickering circuit

* The stabilization factor can be easily shown to be equal to $\frac{R_2}{R_1+R_2} \cdot G \cdot \mu$ to a very near approximation, where μ is the amplification factor of the tube T_1.

In the circuit described above the battery B_2 performs both the functions of the screen battery Es_1 and the grid battery Eg_1. The function of Eg_1 has been to increase the gain of T_2 by making the voltage drop across R_c and so the current through T_2 greater than what is otherwise possible. This battery has to be very carefully insulated and shielded. In the circuit by the author the battery B_2, which replaces this, requires only normal insulation. A leakage from B_2 to the negative line will affect the performance only in that it will place an extra load on the stabilizer.

The results on circuits of this type are shown by the curves in Fig. 8. All the measurements were carried out at low voltages but there is no reason why the circuit should not operate efficiently at high voltages.*

3. IMPROVEMENTS ON TWO-VALVE STABILIZERS

In this section two-valve stabilizer circuits embodying certain new principles are described. The circuits give considerably improved performance and have an extended range of usefulness. They are described under three heads, *viz.*, (*a*) A circuit giving "perfect" stabilization ; (*b*) A circuit for stabilizing the heater currents of vacuum tubes in valve voltmeters, etc. ; and (*c*) A circuit having negative internal resistance.

The mathematical analysis of a circuit embodying all these principles is given. The design of these stabilizers as regards the choice of suitable valves and their operating conditions is also discussed.

(*a*) *A circuit giving "Perfect" stabilization.* The usual two-valve stabilizer circuit like those shown in figs. 7 and 13 cannot give perfect stabilization, *i.e.*, the change in output voltage dV_0 can never become zero for a change dV_i in the input voltage although it may be very small in comparison. The very nature of operation of these circuits demand the presence of some control voltage at the grid of the tube T_2. This control voltage is furnished by the change in the output voltage dV_0 in the usual two-tube circuits. However the necessary control voltage may be easily supplied from the varying input voltage. In that case, no additional change in output voltage will be necessary to provide

* It is necessary to mention here certain important precautions. When voltage changes of the order of millivolts are encountered, it was found absolutely necessary to use fixed resistances, preferably the wire-wound type for R_1 and R_2. Otherwise the spontaneous changes of voltage resulting from the fluctuations of the variable resistance completely swamp the changes which are to be measured. Further it may also be necessary to supply the heater voltage of T_2 from batteries. With two 6SJ7 tubes for T_1 and T_2, it was found necessary to short-circuit the resistance R_1, to use a heater battery and further to take the readings very quickly in order to get a proper measure of the stabilization. The stabilization factor of the circuit was of the order of a million.

extra control and in this sense the circuit may be said to give perfect stabilization. A circuit embodying this principle is shown in fig. 9.

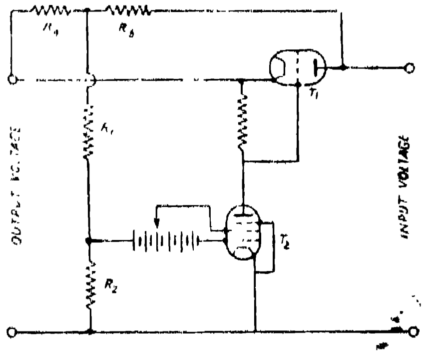

FIG. 9
A circuit capable of "perfect" stabilization

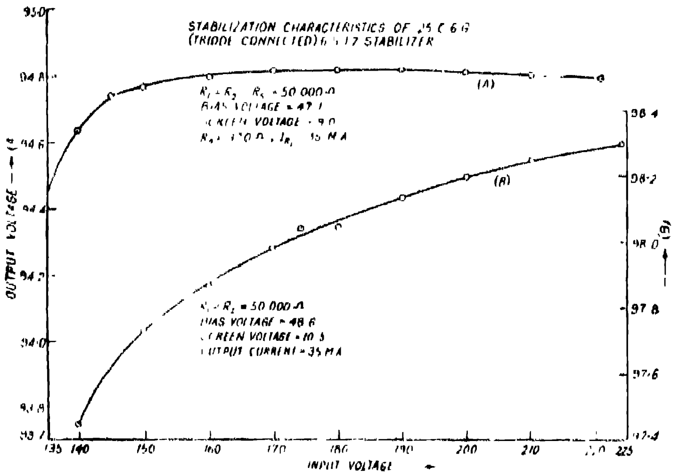

FIG. 10
Performance of the circuit of Fig. 9 compared with that of a straight-forward two-valve circuit

The improvement in performance over the usual circuit will be evident from the curves in fig. 10. It will be seen that the stabilization characteristic of the single-battery two-tube circuit of this type is comparable to that of two-battery circuits shown in fig. 7. Circuits of this type are therefore strongly recommended for all classes of voltage stabilizer work.

(*b*) *A stabilizer for high currents.* A stabilized supply capable of giving currents much higher than can be carried by the tube or tubes in the position T_1 is sometimes necessary. A circuit has been developed from the usual two-tube circuit for this purpose. The most useful form is shown in fig. 11.

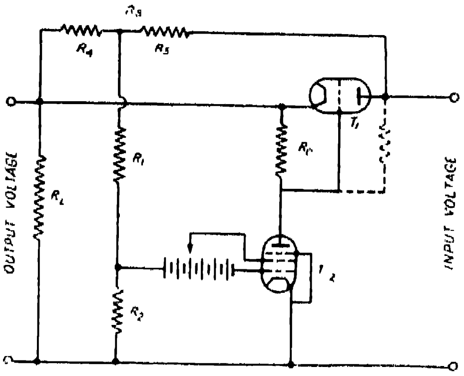

FIG. 11

A stabilizer circuit suitable for large current drains.

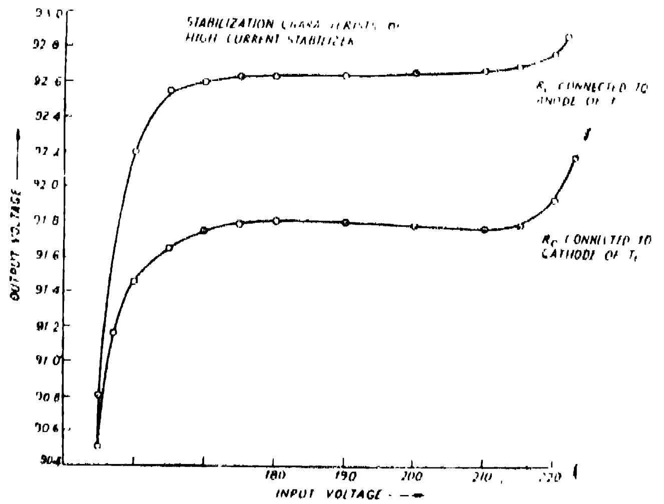

FIG. 12

Stabilization characteristics of a high current stabilizer. The curves are for a circuit using a 25 C6 G for T_1 and 6SJ7 for T_2 delivering an output current of 150 milliamps. R_1 and R_2 were both equal to 50,000 Ω and R_4 was adjusted for perfet stabilization.

From the curves in fig.12 it will be evident that stabilization occurs only over a range of input voltage, that from V_l to V_h. This is because the tubes T_1 and T_2 operate only over this range. At the high voltage end V_h, the whole of the current I_0 that the stablizer has to supply flows through R_s so that the tube T_1 is biased to the non-conducting condition. Hence we have the relation

$$\frac{V_h - V_0}{R_s} = I_0 \; . \qquad \cdots \qquad (10)$$

At the low voltage end V_l, the grid bias of tube T_1 approaches the zero value and cannot change any further, due to the fact that the current through T_2 is zero. In case R_c is connected to the anode of T_1 as shown dotted in Fig. 11, the grid of T_1 goes positive only by the amount that is necessary for it to draw the whole of current that comes through R_c, leaving nothing for T_2. If the current through T_1 at this point be I_m, then we have

$$\frac{V_l - V_o}{R_s} + I_m = I_o. \qquad \ldots \quad (10b)$$

The two equations (10*a*) and (10*b*) locate the points V_h and V_l.

Subtracting equation (10*b*) from equation (10*a*) and simplifying, we get

$$V_h - V_l = I_m . R_s. \qquad \ldots \quad (11)$$

If the mean value of the supply voltage be V_s and if R_s be adjusted such that it falls at the middle point of the horizontal part of the stabilization characteristic, then we can also write

$$\frac{V_s - V_o}{R_s} + \frac{I_m}{2} = I_o.$$

Combining with equation (11) and putting $\frac{V_h - V_l}{V_s} = R$ — the range of stabilization, we get finally

$$R = \frac{I_m}{I_o - I_m/2} \cdot \frac{V_s - V_o}{V_s} . \ 100 \text{ per cent.} \qquad \ldots \quad (12)$$

It will be seen that the range increases as the ratio $\frac{I_m}{I_o - I_m/2}$ increases. The value of $\frac{V_s - V_o}{V_s}$ cannot exceed unity and should peferably be not lower than half. The heater supply of 0.3 ampere tubes may be stabilized over a range of 12% (±6%) using a 25C6G tube for T_1. This is somewhat small compared to that of a commercial "stabilizing transformer" which has a range of about ±15%. However, the stabilizer described here has the advantage of giving much better stabilization than any stabilizing transformer. Also if a wider range is necessary, one may use two 25C6G tubes in parallel for T_1.

(*c*) *A circuit having negative internal resistance.* Stabilizer circuits so far described* all have positive internal resistance, *i.e.*, the voltage at their output terminals decreased with increase in current drain. But in various applications it is highly desirable to have a voltage source capable of maintaining a constant voltage across its terminals even under varying current drains, *i.e.*, a source having zero internal resistance. It may even be desirable to have a source whose terminal voltage should increase with increase in current drain, in order that this increase may compensate for the increased voltage drop across some

* For discussion and reference see *Science and Culture*, **6**, 552 (1941).

other circuit element through which the current may be flowing. In such cases, a voltage source with negative internal resistance is required.

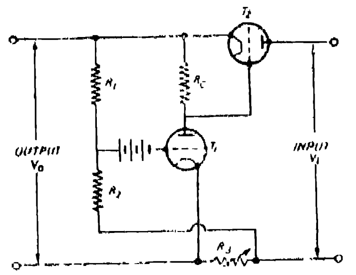

Fig. 13

Typical stabilizer circuit having negative internal resistance.

The resistance R_3 between the cathode of T_2 and the negative line in Fig. 13 brings about this property in two-valve voltage stabilizer circuits. A simple analysis gives the internal resistance R_0 defined by the relation $R_0 = -\left(\dfrac{\partial V_o}{\partial I_o}\right)_{V_i}$ as, $R_0 = \left[\dfrac{1}{G.A.b} - R_3\left(\dfrac{1}{b} - 1\right)\right]$ approximately, ... (13)

where G is the mutual conductance of the tube T_1, A, the amplification given by T_2 and $b = \dfrac{R_2}{R_1 + R_2}$

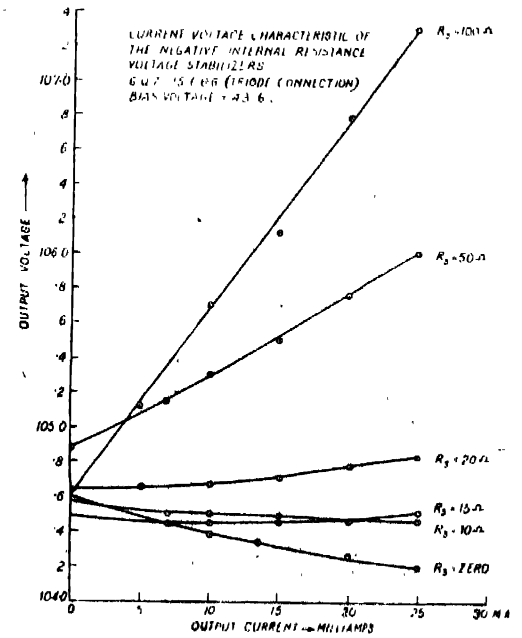

Fig 14

Current voltage curves of the circuit of Fig. 13 using 25C6G and 6Q7 tubes for T_1 d T_2

It will be seen that by a suitable choice of the value of R_3, one can make the internal resistance zero or negative. A negative value of several hundred ohms is not difficult to attain.

The stabilization factor of the circuit remains practically unaffected by the inclusion of R_3 and is approximately given by

$$S_0 = b.A.\mu$$

where μ is the amplification factor of the tube T_1.

A number of voltage current curves using two triodes for T_1 and T_2 in the circuit of fig. 13 is shown in fig. 14.

A voltage stabilizer with zero or negative internal resistance has great possibilities as a bias supply system of high power class B audio amplifiers. The grid current which flows in these systems when the grid swing is positive increases the negative bias. This increase of negative grid bias with the grid swing increases the distortion in the audio output. As a result the bias supply system has to be so designed that they present a very low internal resistance in order that the rise in the negative bias may be very small. Such a design is expensive. The problem can better be solved using a voltage stabilizer with zero internal resistance. It may be supplied by an ordinarily designed transformer-rectifier-filter system. The stabilizer will also smooth out the residual ripple in the bias voltage to a very low value.

The average anode current of a class B audio amplifier increases with the grid swing. This reduces the D.C. anode voltage and brings about further distortion in the audio output. This distortion due to anode circuit regulation can be minimized by making the grid bias diminish as the average anode current increases. It has been observed by Rockwell and Platts[5] that the distortion is also prevented

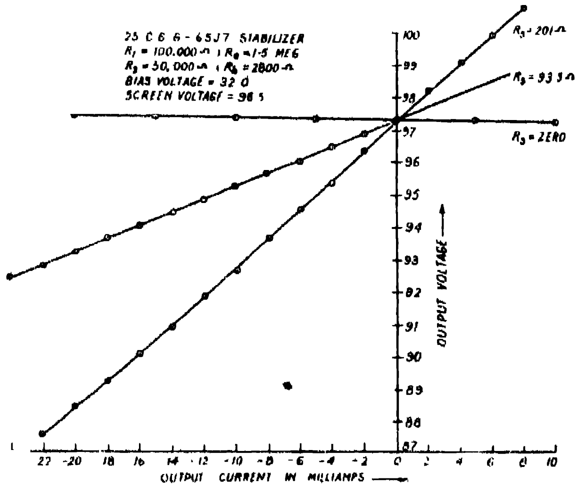

FIG. 15
Current-voltage characteristics of the circuit proposed for use as a bias supply system of class B amplifiers

in a great measure if the grid bias is made to diminish with the grid current instead of the anode current. A voltage stabilizer having negative internal resistance, such as that shown in fig. 13 may be expected to perform this function. The circuit, however, has got to be modified by the inclusion of a bleeder resistance R_b across R_1 and R_2 or across the output terminals. For as the current that is forced into the system exceeds the value

$$I_m = \frac{v_o}{R_b} \qquad \ldots \quad (14)$$

the current I_1 through the tube T_1 becomes equal to zero and the circuit ceases to function as 'G' and 'a' both are zero in this condition. It is evident that the internal resistance in this condition, of the two circuits, becomes equal to $(R_b + R_3)$ and R_b respectively. (See eq. 20.) For bias supply systems of class B amplifiers, I_m must exceed the maximum grid current

$$I_m \gtreqqless I_g \qquad \ldots \quad (15)$$

and the tube or tubes for T_1 should be chosen keeping this in mind. The bias voltage v_o being known R_b should be calculated from (14) and (15).

(*d*) *Mathematical theory of the two-valve stabilizers.* The mathematical theory of the most general form of two-valve stabilizer circuit as shown in Fig. 16 is worked out below.

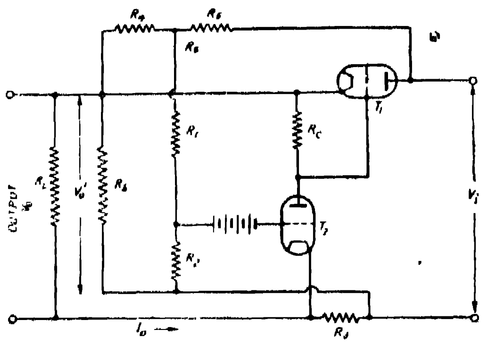

FIG. 16

Illustrating the general form of two-valve stabilizer circuit

The stabilization factor "S". Let the input voltage V_i change by an amount δV_i and let the resulting change in output voltage be δV_o. Let V_o', the voltage across R_b, change by an amount $\delta V_o'$. Then we can write for the grid voltage of T_2

$$\delta v_2 = b\{\delta V_o' + \rho(\delta V_i - \delta V_o')\} - R_3 \delta I_o$$

v_o is the output voltage when the current forced into the system is equal to I_m.

where $b = \dfrac{R_2}{R_1+R_2}$ and $\rho = \dfrac{R_4}{R_4+R_5}$; δI_0 the change in current through R_L is equal to $\dfrac{\delta V_0'}{R_L+R_3}$. Hence $\delta v_2 = b\left\{\delta V_0'\left(1-\rho-\dfrac{R_3/b}{R_L+R_3}\right)+\rho\delta V_i\right\}$.

The change in grid voltage of T_1 is, therefore,

$$\delta v_1 = -gR_c\left[b\left(1-\rho-\frac{R_3/b}{R_L+R_3}\right)\delta V_0'+b\rho\delta V_i\right]-\frac{R_c}{R_c+R_r}\,\delta V_0'$$

$$= -k'\delta V_0'-k''\delta V_i$$

where

$$\left.\begin{aligned} k' &= gR_cb\left(1-\rho-\frac{R_3/b}{R_L+R_3}\right)+\frac{R_c}{R_c+R_r} \\ k'' &= gR_cb\rho. \end{aligned}\right\} \quad \ldots \quad (17)$$

and

The change in total current, since the change through R_s is equal to

$$\frac{1}{R_s}(\delta V_i-\delta V_0'),$$

$$\delta I = -Gk'\delta V_0'-Gk''\delta V_i+\left(a+\frac{1}{R_s}\right)\left(\delta V_i-\delta V_0'\right).$$

This produces a change of voltage $\delta V_0'$ across R_b which may be written as

$$\delta V_0' = \frac{R_b(R_L+R_3)}{(R_b+R_L+R_3)}.\ \delta I$$

$$= \frac{R_b(R_L+R_3)}{(R_b+R_L+R_3)}\left[-Gk'\delta V'_0-Gk''\delta V_i+\left(a+\frac{1}{R_s}\right)\left(\delta V_i-\delta V'_0\right)\right]$$

whence

$$\frac{\delta V_i}{\delta V'_0} = \frac{1+\dfrac{R_b(R_L+R_3)}{R_b+R_L+R_3}\left[Gk'+a+\dfrac{1}{R_s}\right]}{\dfrac{R_b(R_L+R_3)}{R_b+R_L+R_3}\left[a+\dfrac{1}{R_s}-Gk''\right]}.$$

Also $$V_0 = (V'_0-R_3I_0)$$

so that $\delta V_0 = \delta V'_0 - R_3\delta I_0, \quad = \dfrac{R_L}{R_L+R_3}\,\delta V_0'.$

Therefore the stabilization ratio S_0 is equal to

$$\frac{\delta V_i}{\delta V_0} = \frac{1+\dfrac{R_b(R_L+R_3)}{R_b+R_L+R_3}\left[Gk'+a+\dfrac{1}{R_s}\right]}{\dfrac{R_b(R_L+R_3)}{R_b+R_L+R_3}\left[a+\dfrac{1}{R_s}-Gk''\right]}\cdot\frac{R_L+R_3}{R_L} \quad \ldots \quad (18)$$

The value of ρ for perfect stabilization may thus be found. The stabilization ratio approaches infinity when

$$a+1/R_s \rightarrow Gk'' \quad Gk'\rho \quad \text{or} \quad 1/\rho \rightarrow \frac{Gk'+a+1/R_s}{a+1/R_s}-1. \qquad \dots \quad (19)$$

Now $\dfrac{Gk'+a+1/R_s}{a+1/R_s}$ is very nearly equal to the stabilization factor when R_4 and R_3 are zero. This may be found out experimentally when equation (19) will give the value of ρ.

Internal Resistance R_0. When a current δI_0 is drawn, let the change in output voltage be δV_0 and the change in voltage across R_b be $\delta V_0'$. Then we have, for the change in grid voltage of T_2,

$$\delta v_2 = b\{\delta V_0' - \rho\delta V_0'\} - R_3\delta I_0.$$

The change in grid voltage of T_1 is, therefore,

$$\begin{aligned}\delta v_1 &= -gR_c[b(1-\rho)\delta V_0' - R_3\delta I_0] - \frac{R_c}{R_c+R_r}\cdot\delta V_0' \\ &= -A[b(1-\rho)\delta V_0' - R_3\delta I_0]\end{aligned}$$

neglecting $\dfrac{R_c}{R_c+R_r}\cdot\delta V_0'$ and putting $g\,R_c = A$.

The change in anode current of T_1 is therefore equal to

$$\delta I_a = -AG[b(1-\rho)\delta V_0' - R_3\delta I_0] - a\delta V_0'.$$

The change in current through R_s is equal to $-\dfrac{\delta V_0'}{R_s}$. The change in current through R_b is equal to $\dfrac{\delta V_0'}{R_b}$. Hence the change in output current

$$\delta I_0 = -\left[AGb(1-\rho)+a+\frac{1}{R_s}+\frac{1}{R_b}\right]\delta V_0' + AGR_3\delta I_0$$

or

$$\delta V_0' = -\frac{[1-AGR_3]}{\left[AGb(1-\rho)+\left(a+\dfrac{1}{R_s}+\dfrac{1}{R_b}\right)\right]}\delta I_0$$

Now

$$\delta V_0 = \delta V_0' - R_3\delta I_0$$

Hence

$$R_0 = -\left(\frac{\delta V_0}{\delta I_0}\right)_{v_i} = \frac{[1-AGR_3]}{\left[AGb(1-\rho)+\left(a+\dfrac{1}{R_s}+\dfrac{1}{R_b}\right)\right]} + R_3 \qquad (20)$$

(*c*) *General consideration on the design of two-valve Stabilizers.* It is possible to obtain zero internal resistance and infinite stabilization ratio by using any combination of tubes for T_1 and T_2 in the circuit of Fig. 16. These conditions will, however, be satisfied only over a narrow range of input voltages unless the tubes are properly selected and operated. The performance of the stabilizer under actual operating conditions is better described by the stabilization and current-voltage characteristics rather than by the stabilization ratio and internal resistance at certain points.

Good stabilization and current-voltage characteristics can be secured only if these characteristics are inherently good, *i.e.*, if the characteristics without R_4 and R_3 are linear and have a small slope. The function of R_4 and R_3 is only to change the slope of the curves so as to make them horizontal. If the slope is not small so that the correction required is large and if the curve is not linear initially, the final characteristic, although it may be made horizontal at certain points, will not be so over a wide range.

The inherent characteristics will be good if the tubes T_1 and T_2 are so selected and operated that the quantity G.A.b is large and has as constant a value as possible over the whole range of plate currents of the tube T_1. $b = R_2/(R_1 + R_2)$ has a constant value which cannot exceed unity. It is also usually limited to a small fraction inasmuch as it is also equal to V_c/V_0 and the battery voltage V_c cannot conveniently and economically have a value much greater than 100 volts. The tube T_1 should be selected as one having a high, and as far as possible a constant, value of the mutual conductance G. Beam tubes, because of their uniform electrode structure and high mutual conductance are most suited for this purpose. These may be used with the screen grid connected to the anode so as to make them virtually a triode. The tube T_2 should be a sharp-cut-off pentode. A sharp-cut-off pentode gives much greater amplification than any triode or pentode of the remote-cut-off type. The amplification 'A' however decreases as the voltage drop across R_c, *i.e.*, the grid bias of T_1, diminishes. But the mutual conductance G of the tube T_1 increases as the plate current increases due to the reduction of the grid bias. As a result of this, the product GA tends to be more constant over a range of plate currents of the tube T_1. This makes the current-voltage characteristic of stabilizers of both types and the stabilization characteristic of the high current stabilizer more linear than is otherwise possible.

The tube T_2 should be operated with a low screen voltage,* of the order of 10-20 volts, and a high value of the coupling resister R_c. This enables it to give a greater and more constant amplification.

* With a stabilizer using 25C6G and 6SJ7 tubes for T_1 and T_2 respectively a screen voltage of 4.5 volts gave the best stabilization curve. The stabilization characteristic deteriorated rapidly below this optimum and relatively slowly above this.

Although R_r forms in effect the grid leak of the tube T_1, its value need not be limited to the usual $\frac{1}{4}$MΩ or $\frac{1}{2}$MΩ recommended by tube manufacturers and may with advantage be considerably exceeded. Any tendency towards the diminution of grid voltage due to collection of positive ions, etc., by the grid and the resulting increase in anode current, increases the output voltage, a fraction of which is applied to the grid of T_2. The anode current of T_2 rises in consequence and takes away the major part of the positive ion current. As a result of this self-adjusting action a much higher value than is recommended by tube makers may be tolerated for R_r. Higher values of R_r are advantageous in that they enable the tube T_2 to give a greater amplification.

The battery voltage V_r and so the value of "*b*" should be as large as is economically and conveniently possible. This not only gives a better inherent stabilization and current-voltage characteristic but also makes the output voltage less dependent on the filament voltage of T_2.

4. EFFECT OF SOURCE RESISTANCE IN MODIFYING THE PERFORMANCE OF A VOLTAGE STABILIZER

(a) Nature of the problem. The performance of voltage stabilizers is modified if the primary source has appreciable internal resistance. This effect has been studied by Hunt and Hickman.[1] We are presenting here a more general analysis which is also more simple and straightforward.

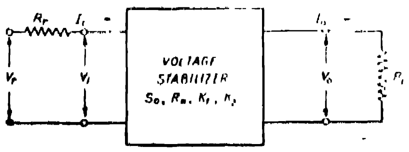

FIG. 17
Equivalent circuit of the stabilizer together with the primary source

The overall stabilization ratio S and internal resistance R of the stabilizer system, when the primary source has an internal resistance R_r, may be defined as

$$S = \frac{dV_r}{dV_0} \qquad \cdots \quad (21)$$

and

$$R = -\left(\frac{\partial V_0}{\partial I_0}\right)_{v_r}, \qquad \cdots \quad (22)$$

whereas the corresponding ratios for the voltage stabilizer alone are

$$S_0 = \frac{dV_i}{dV_0} \qquad \cdots \quad (23)$$

and

$$R_0 = -\left(\frac{\partial V_0}{\partial I_0}\right)_{v_i}, \qquad \cdots \quad (24)$$

v_r denoting the e.m.f. of the source.

Our problem is to express the values of S and R in terms of the constants of the voltage stabilizer, the source resistance R_r and the load resistance R_l.

(*b*) *Overall Stabilization Ratio.* We have the overall stabilization ratio

$$S=\frac{dV_r}{dV_0},$$

which may be written with the help of equation (23) as

$$\left(\frac{dV_r}{dV_i}\right).\,S_0. \qquad \ldots \quad (25)$$

Now we have,

$$V_r=V_i+R_rI_i \qquad \ldots \quad (26)$$

where I_i is the current taken in by the voltage stabilizer. This can be written as

$$I_i=I_0+K_1V_i+K_2V_0, \qquad \ldots \quad (27)$$

where K_1 and K_2 are the leakage conductances present across the input and output terminals of the voltage stabilizer.

Hence, substituting in (26) we get after simplification

$$V_r=V_i(1+R_rK_1)+\left(\frac{R_r}{R_L}+R_rK_2\right)V_0,$$

whence

$$\frac{dV_r}{dV_i}=1+R_rK_1+\left(\frac{R_r}{R_L}+R_rK_2\right)\frac{1}{S_0}. \qquad \ldots \quad (28)$$

Substituting this in (25), we get

$$S=S_0(1+R_rK_1)+\frac{R_r}{R_L}+R_rK_2. \qquad \ldots \quad (29)$$

This gives the overall stabilization factor "S" in terms of the constants of the stabilizer S_0, K_1, K_2, the source resistance R_r and the load resistance R_L.

(*c*) *Overall Internal Resistance.* When an excess current δI_o is drawn, the change in output voltage δV_o may be written as

$$\delta V_o=\left(\frac{\partial V_o}{\partial I_o}\right)_{V_i}\delta I_o+\left(\frac{\partial V_o}{\partial V_i}\right)_{I_o}\delta V_i$$

or

$$\left(\frac{\partial V_o}{\partial I_o}\right)_{V_r}=\left(\frac{\partial V_o}{\partial I_o}\right)_{V_i}+\left(\frac{\partial V_o}{\partial V_i}\right)_{I_o}.\left(\frac{\partial V_i}{\partial I_o}\right)_{V_r}. \qquad \ldots \quad (30)$$

We are to find the value of $\left(\frac{\partial V_o}{\partial V_i}\right)_{I_o}$. For this we note

$$\frac{dV_o}{dV_i}=\left(\frac{\partial V_o}{\partial V_i}\right)_{I_o}+\left(\frac{\partial V_o}{\partial I_o}\right)_{V_i}.\left(\frac{\partial I_o}{\partial V_i}\right),$$

whence $$\left(\frac{\partial V_o}{\partial V_i}\right)_{I_o} = \left(\frac{dV_o}{dV_i}\right) - \left(\frac{\partial V_i}{\partial I_o}\right)_{V_i}\left(\frac{\partial I_o}{dV_i}\right) = \frac{1+R_o/R_L}{S_o}. \quad \ldots \quad (31)$$

The change in voltage δV_i, V_r remaining constant due to a change of output current δI_o may be obtained as follows :

We have, $$\delta V_i = -R_r \, \delta I_i$$

Now $$I_i = I_o + K_1 V_i + K_2 V_o = I_o + K_1(V_r - R_r I_i) + K_2 I_o R_L\,,$$

whence $$\left(\frac{\partial I_i}{\partial I_o}\right)_{V_r} = \frac{1+K_2R_L}{1+K_1R_r}$$

and $$\left(\frac{\partial V_i}{\partial I_o}\right)_{V_r} = \left(\frac{\partial V_i}{\partial I_i}\right)\left(\frac{\partial I_i}{\partial I_o}\right)_{V_r} = -R_r \cdot \frac{1+K_2R_L}{1+K_1R_r}. \quad \ldots \quad (32)$$

Substituting (31) and (32) in (30) the overall internal resistance comes out as

$$R = -\left(\frac{\partial V_o}{\partial I_o}\right)_{V_r} = R_o + \frac{(1+R_o/R_L)(1+K_2R_L)}{(1+K_1R_r)} \cdot \frac{R_r}{S_o}. \quad \ldots \quad (33)$$

It will be observed from equations (28) and (33) that the source resistance has only very slight effect on the performance of stabilizers having high stabilization ratios.

CONCLUSION

In the single-valve circuit described by Neher and Pickering, the screen grid may be conveniently supplied from a potential divider across the input terminals instead of from the usual dry battery. The fluctuations of the screen voltage with the input voltage may then be greatly reduced because the screen grid current fluctuates with the input voltage and this produces a voltage fluctuation in the opposite sense. Further, the performance is considerably improved if the screen grid potential fluctuates in a prescribed manner. In fact, the performance is better than that of a circuit using a dry battery for the screen supply.

It is possible to eliminate two of the four dry batteries in the two-valve circuit described by Neher and Pickering by an improved method of connection, whereby each battery is made to perform the function of two batteries simultaneously.

The two-valve degenerative amplifier type of stabilizer can be made to give "perfect" stabilization and "zero" or negative internal resistance. This is achieved by applying to the grid of the amplifier tube, over and above the usual control derived solely from the output voltage, small voltages which are proportional to the input voltage as also to the output current. The performance of the resulting circuits is superior in almost every respect to other types of stabilizer circuits. Such a circuit, with negative internal resistance is very useful in reducing distortion of class B power amplifiers.

The high current stabilizer which has been developed from the two-valve stabilizer circuit gives better stabilization than any "stabilizing transformer" or "baretter" tube and may be used for supplying the heaters of thermionic tubes employed in sensitive valve voltmeters.

ACKNOWLEDGMENTS

The author wishes to express his sincere gratitude to Professor S. K. Mitra for his kind interest and to Dr. H. Rakshit for his constant advice during the progress of the work.

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